

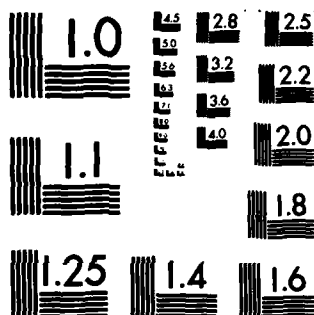
APPLICATIONS OF COMPOUND EYE CONFIGURATIONS TO SMART
SENSOR DESIGN(U) NAVAL RESEARCH LAB WASHINGTON DC
W H CARTER 26 FEB 85 NRL-MR-5480

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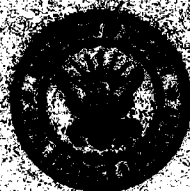
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REPORT DOCUMENTATION PAGE				
1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED		1b. RESTRICTIVE MARKINGS		
2a. SECURITY CLASSIFICATION AUTHORITY		3. DISTRIBUTION/AVAILABILITY OF REPORT		
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE		Approved for public release; distribution unlimited.		
4. PERFORMING ORGANIZATION REPORT NUMBER(S) NRL Memorandum Report 5480		5. MONITORING ORGANIZATION REPORT NUMBER(S)		
6a. NAME OF PERFORMING ORGANIZATION Naval Research Laboratory	6b. OFFICE SYMBOL (If applicable) Code 7740	7a. NAME OF MONITORING ORGANIZATION Office of Naval Research		
6c. ADDRESS (City, State, and ZIP Code) Washington, DC 20375-5000		7b. ADDRESS (City, State, and ZIP Code) Arlington, VA 22217		
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Office of Naval Research	8b. OFFICE SYMBOL (If applicable) Code 100X	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER		
8c. ADDRESS (City, State, and ZIP Code) Arlington, VA 22217		10. SOURCE OF FUNDING NUMBERS		
		PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.
				WORK UNIT ACCESSION NO. 77-1280-F-4
11. TITLE (Include Security Classification) Applications of Compound Eye Configurations to Smart Sensor Design				
12. PERSONAL AUTHOR(S) Carter, William H.				
13a. TYPE OF REPORT Final	13b. TIME COVERED FROM 9/83 TO 12/83	14. DATE OF REPORT (Year, Month, Day) 1985 February 26	15. PAGE COUNT 24	
16. SUPPLEMENTARY NOTATION				
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)	
FIELD	GROUP	SUB-GROUP		
			Compound eye Seeker guidance	
			Smart sensor Detectors	
19. ABSTRACT (Continue on reverse if necessary and identify by block number)				
<p>The application of compound eyes to the design of smart sensors is reviewed. Special attention is given to features of this class of eyes which might be of particular advantage in these applications. It was found that the compound eyes are much more compact than the human eye, but some suffer from a lack of resolution and sensitivity. Several specific suggestions are made for the application of features from compound eyes to smart sensor systems.</p>				
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT <input type="checkbox"/> DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED	
22a. NAME OF RESPONSIBLE INDIVIDUAL William H. Carter			22b. TELEPHONE (Include Area Code) (202) 767-2453	22c. OFFICE SYMBOL Code 7740

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APPLICATIONS OF COMPOUND EYE CONFIGURATIONS TO SMART SENSOR DESIGN

I. Introduction

The compound eye of the insects (and some other lower creatures) has long excited the curiosity of men. Why are these creatures equipped with eyes so different from us? Is this simply a result of a different evolutionary path, or do these eyes have some special advantages over ours? The possibility that compound eyes might provide the owner with some special capability is particularly interesting. Could we use some feature from the compound eye to improve the design of the light detection systems for smart sensors? These are the questions that motivate this study. The author thanks Dr. William J. Condell for suggesting the study, for many helpful comments, and for supporting the work at NRL.

This report is divided into three sections. The first section describes some of the features of the compound eye which are both novel to this type of eye, and of some interest to the systems designer. The second section contains a mathematical analysis of some of these features. And, the final section discusses some ideas from this study that relate to the design of light sensors for seekers.

II. Features of the Compound Eye

All compound eyes are characterized by an array of "little eyes", as shown in the Fig. 1, which are known as ommatidia.

Manuscript approved June 27, 1984.

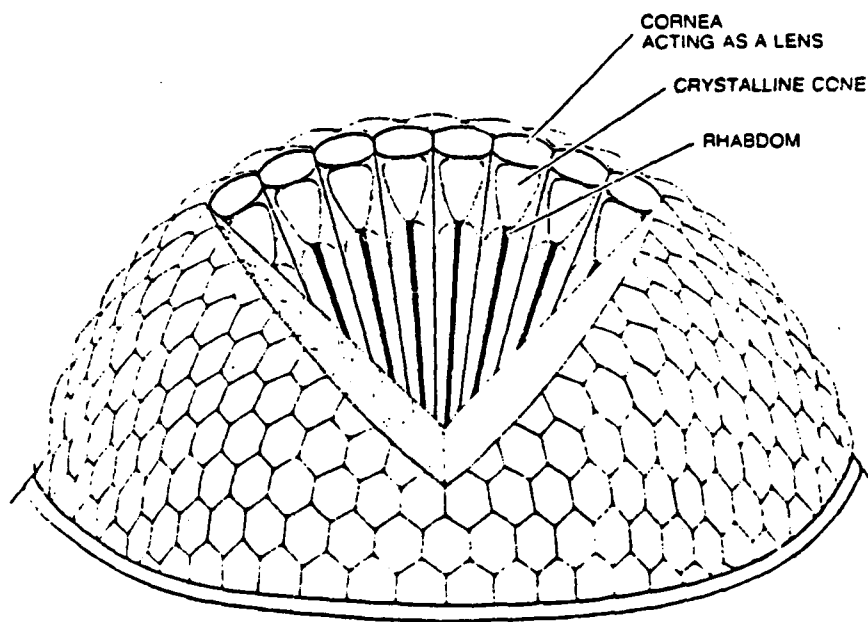


Fig. 1. Diagram of a typical compound eye (from Ref. 1).

Each of the ommatidia is composed essentially of a lens, a light guiding structure, and a group of detector cells. The guiding structure is usually combined with several detector cells into a structure called the rhabdom. A typical rhabdom is composed of a simple gradient index light guide with six or seven photoreceptor cells called rhabdomeres inside. For a detailed anatomical description of the compound eye the interested reader is referred to the many review articles on the subject.^{1,2,3}

A feature that most all compound eyes have in common is the gradient index lens. In 1891 Sigmund Exner^{3,4} published a monograph that put forth a solution to the difficulty scientists were having understanding the function of the rather strange lenses found in these eyes. The index of refraction difference found between the lens material and air is only minimal. Thus refraction of light at a curved lens-air interface would be much too small to focus the light to an image in the usual way. He suggested instead that the lens worked as a "lens cylinder" or, as it would be called today, a gradient index lens. This concept for a lens was not new even in Exner's day, but until very recently methods for manufacturing such lenses in a practical manner were virtually nonexistent. Recent research into fiber optic communications has lead to a few practical methods for producing gradient index lenses.⁵ Some ideas for applying such lenses to guided weapons will be taken up in the next sections.

The compound eye is not simply a particular eye structure, but rather a class of eye structures which have greatly different features. This is illustrated by the two very different types of ommatidia shown in Figs. 2. Figure 2a shows a typical ommatidia

from a "superposition" eye, whereas Fig. 2b shows one from an "apposition" eye. The mechanism for image formation in these two types of eyes appears to be very different even though they are both classified as compound eyes.

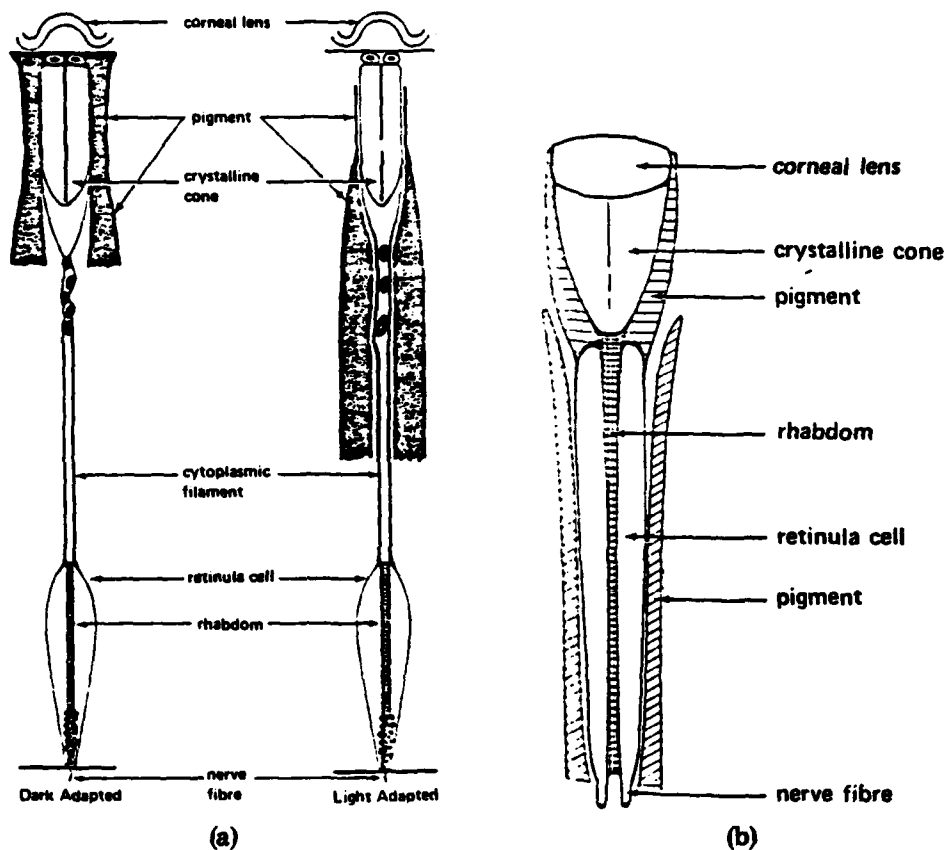


Fig. 2. Diagram of typical ommatidia from compound eyes (from Ref. 11).

The function of the apposition eye seems to be the best understood. The ommatidia that comprise these eyes each respond to light incident on the eye from a different direction. They appear to respond independently, in such a manner that light collected by the lens of one ommatidium does not reach the photodetectors of any of its neighbors. The superposition eye behaves quite differently in this respect. Here, the light from the entire lens array appears to fall on the photoreceptor array collectively in some manner. The exact mechanism for this does not appear to be well understood, but the basic idea dates back to an experiment conducted by Exner,⁴ almost a century ago, in which he demonstrated that the lens array, when separated from the underlying tissues, is capable of forming an erect image onto a plane behind the plane of the array in the approximate position the photodetectors usually occupy. Since this experiment there has been considerable controversy over the manner in which these eyes function. Some recent workers believe that the lens array acts like an array of gradient index lenses to form the image over the photoreceptor array. Such an eye has definite advantages over the apposition eye in respect to sensitivity and resolving small detail. This will be analyzed in more detail later in this report. Other workers have pointed out that in at least some compound eyes which appear superficially to be superposition eyes the "clear zone" between the lens array and the photoreceptor array is traversed by light guides which direct the light from each lens to a particular rhabdom. Thus, for such eyes the ommatidia work independently in such a manner that the eye actually works as an apposition eye.⁶ A currently popular

point-of-view is that "most if not all" insect eyes with clear zones between the lens array and rhabdoms, act as true superposition eyes at night when the light guiding fibers act minimally, but as apposition eyes during the day when pigment movement into the clear zone makes the fibers effective light guides(see Ref. 3,p. 683). Thus at night the eyes act to maximize quantum efficiency, while during the day they maximize resolution.

It has been suggested by Land³ and others that in some compound eyes there are really no effective lenses at all, but that the image is formed over the rhabdoms by an array of square mirror tubes as illustrated in Fig. 3. This type of superposition eye has the advantage to us of being much easier to fabricate than one based of gradient index lenses (Ref. 3,p. 685).

Another feature of the insect compound eye that could be of use to the design engineer is the corneal nipples which cover the outer surface of the lens of each ommatidium (see Ref. 2, p. 763). The corneal nipples are a hexagonal array of conical protuberances, about 0.2 microns from tip to base and from center to center as shown in Fig. 4. These act as an antireflection coating to improve the quantum efficiency of the eye. A similar technique has been used in the design of some microwave lenses. In some insect eyes the nipples have been found to reduce the reflection losses from the air-cornea interface by more than 1000.

An additional increase in quantum efficiency is obtained in some insect eyes due to a reflecting tracheole layer just under-

lying the rhabdoms.⁷ This is similar in function to the reflecting layer (tapetum lucidum) just below the retina of some higher animals such as the cat. Humans and other animals with less sensitive eyes (quantum efficiencies of only about 5%) have a light absorbing sclerotic coat below the retina. In animals with a reflecting layer below the photoreceptors, light that is not absorbed by the photoreceptors on the first pass is reflected back into them for a second try, thus increasing the quantum efficiency.⁸

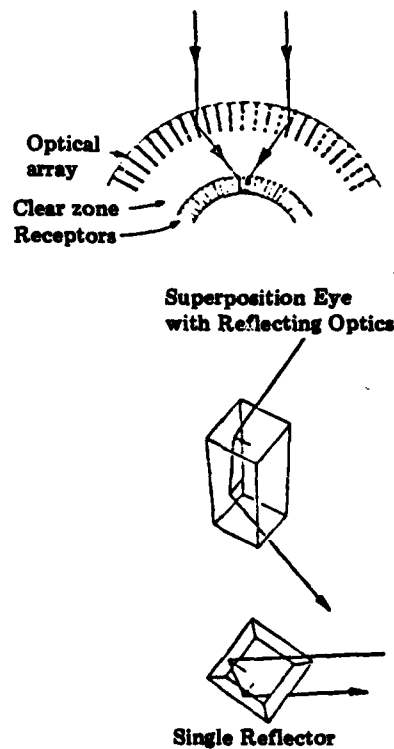


Fig. 3. Diagram of a superposition eye using reflecting optics.

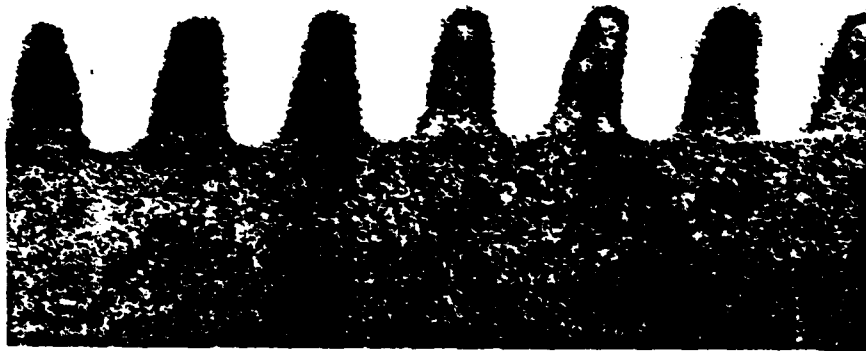


Fig. 4. Electron micrograph showing the corneal nipples at the interface between the air and cornea in a monarch butterfly (from Ref. 2).

III. Mathematical Analysis of Some Compound Eye Features

Some of the features that we have found in compound eyes which have possible uses in the design of guidance systems have not been well-analyzed in the literature which has come to our attention. It therefore appears useful to consider these features more carefully here.

The chief advantage of the compound eye for insects appears to be the size. A compound eye only takes up a thin layer of the order of a millimeter or less in depth over the surface of the insect's head. At the same time, this eye covers a significant portion of the head. Thus the compound eye is well-suited to the small size of the animal. The price that is paid in the apposition eye for the small size appears to be both resolution and sensitivity as we shall discuss in the following. The exact working of the insect eye appears to be not well understood. In fact there is a controversy over the very existence of the so called "superposition" eye. Some scientists prefer to call eyes with structure like that shown in Fig. 1, "clear zone eyes,"

because of this controversy. It is thought by many that a compound eye works as a motion detector rather than an image-forming device because of the poor resolution and sensitivity. The concept of the "superposition" eye, if correct, would suggest that at least some insect eyes could have higher resolution and sensitivity than was thought. These ideas will be discussed in more detail in this section.

A chief limitation of the apposition compound eye is the diffraction limit on resolution imposed by the aperture of a single ommatidial lens. Because the light from each ommatidium in the apposition eye works independently there is no interference between light passed by different ommatidial apertures. This lack of interference gives rise to a fundamental angular resolution limit θ (half the angle that the smallest resolvable interval subtends from the eye's aperture) that is determined only by the diameter d of a typical lens and the wavelength λ of light by the well known equation

$$\theta = 1.22 \lambda / d. \quad (1)$$

This limitation is a direct result of the wave nature of light not the eye itself and is a manifestation of the uncertainty principle of quantum mechanics. Lens aberrations, defocus, rhabdom size, or other eye dependent property can decrease the resolution but never increase it. For a typical value of $d = 28.5$ microns found in the high resolution ommatidia of some insect eyes and $\lambda = .6$ microns (red light) Eq. (1) gives an angular resolution limit of $\theta = 25.6$ mr. This can be

compared with the resolution limit imposed by the human eye. The aperture of the human eye varies with the degree of dark adaptation. When the eye is fully dark adapted the aperture can be as large as 5600 microns, but experiments suggest that lens aberrations and photoreceptor density (i.e. spacing) reduce the resolution under these conditions. However, evidence suggests that the eye is diffraction limited when the aperture is reduced to about 2350 microns (for red light, see Ref. 9, p. 175). Thus from Eq. (1) we obtain a diffraction limit of only $\theta = 0.32$ mr, almost two orders of magnitude better than the insect eye.

Clearly the resolution limit for an apposition eye is much poorer than the resolution we humans are accustomed to expect from our eyes. A rather clever illustration of this fact was published by Kirschfield¹⁰ and is shown in Fig. 5. Direct measurement of the resolution limit for a single ommatidia in the eye of a fly yields $\theta = 17.5$ mr which is in rough agreement with the diffraction limit calculated above.¹² The somewhat smaller experimental value must be due to either a somewhat larger value of d or smaller value for the average wavelength used in the experiment. Clearly the fly's eye is close to the diffraction limit.

The second major limitation of the apposition eye is the low sensitivity. The ommatidia that make up the eye are looking in different directions. It is not necessary that the lens in each ommatidium form an image over its rhabdom since each rhabdom only contains six or seven photoreceptors. These lenses act only to collect the light falling over the ommatidia aperture and,

together with the underlying structures, to concentrate as much of the light as possible onto the photoreceptors for detection.

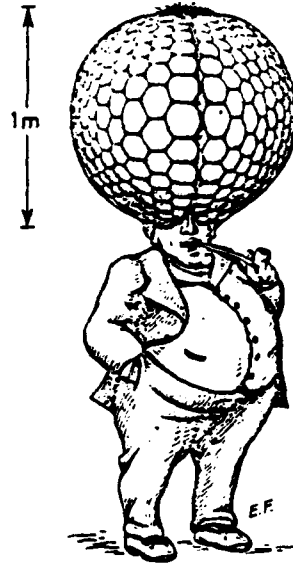


Fig. 5. Human equipped with the smallest compound eye which has the same resolution as a diffraction limited human eye (from Ref. 10).

However, the lenses, because of their small size do not collect as much light as those in the eye of a larger animal such as a human. To understand this it is useful to consider a very small source of light illuminating a compound eye such that only one ommatidia can receive the light. Actually there is evidence of some overlap in the ommatidia fields of view, but we can neglect this to first order. Then the fraction of the light radiated by the source that can enter the aperture of the ommatidia is

$$f = (d / 4R)^2 \quad (2)$$

where R is the distance from the source to the eye. If a human eye or any optical system with a round aperture of diameter d'

were similarly illuminated by the same source, and from the same distance R , then Eq. (2) can still be applied so that the ratio of light energy received by the optical system to that received by the compound eye is

$$r = (d/d')^2 \quad (3)$$

In comparing the compound eye with the human eye with the typical values $d = 50$ microns and $d' = 5600$ microns, we find from Eq. (3) that $r = 8 \times 10^{-5}$, a truly significant sensitivity loss. In comparing the compound eye with a large seeker with an aperture of 10 cm, we find that $r = 2.5 \times 10^{-7}$. This is clearly strong evidence against the use of apposition compound eyes in the design of seekers working with targets which are not many orders of magnitude brighter than their background. As we will now show, the same objection does not hold for a superposition eye.

The superposition eye works in an entirely different way than an apposition eye despite a superficial resemblance. The ommatidia in a superposition eye do not work independently, but rather in concert. The array of lens elements form a single composite lens array that forms a single image over the rhabdom plane. We will assume here that light from different ommatidia superimpose coherently. Then the lens array acts very similarly to the single lens in the simple eye except that it is the effective aperture rather than the actual physical aperture that determines the resolution. The effective aperture at some particular point P in the rhabdom plane is the same as the area A in the lens plane over which light is directed to that point.

Since all of the lenses which contribute light to the point P do not necessarily do so equally, the aperture is generally a shaded aperture. If we assume that the effective aperture can be treated as uniform, round, and with a diameter which is about N times the diameter of a rhabdom lens, then from Eq. (1) we see that the angular resolution is $1/N$ times as much as for a similar apposition lens. Thus if the effective aperture is 100 lens elements across Eq. (1) gives $\theta = .256$ mr, which is roughly equivalent to the human eye. The increase in sensitivity is still greater for by Eq. (2) we see that f is increased by a factor of N squared. Thus in comparing such an eye to the human eye we have from Eq. (3) the energy ratio $r = 0.8$, the eyes are again almost equivalent. If the superposition eye is almost equivalent in resolution and sensitivity to a simple eye what then of the size advantage? Does it still exist? Can we make some useful application of it? I believe the answer to all of these questions is yes.

A principal reason that the superposition compound eye can be made smaller in depth into the head than a conventional simple eye is the use of gradient index lens elements. It has been known for a long time¹³ that the focal length of some gradient index lenses can be made at least as much as $3/4$ smaller than that of a simple lens with the same central index of refraction. The design of gradient index lenses is a new field, which is complicated by fabrication difficulties and an evolving and complicated theoretical foundation. A careful evaluation of this technology for application to seeker design, would be very interesting and potentially very useful, but lies beyond the

present scope of this study. We will, however, look at a few of the simpler aspects of gradient index lenses which might relate to seeker design in the next section.

IV. Applications of Features from Compound Eyes to Seeker Design

From the definitely poor resolution and sensitivity of apposition compound eyes, it is not clear that they are well suited for application in the design of seekers. Therefore, we will restrict our consideration here to the superposition eye, and to special features in some compound eyes which might be useful.

The superposition eye appears to require some sort of gradient index lens array. Until very recently such arrays were not available. Recently several manufacturers, such as the Nippon Sheet Glass Company, LTD., have begun production of such arrays. This company in particular produces gradient index lens arrays for use in electrophotographic copiers under the trade name Selfoc Lens Array. These arrays are intended for use in copiers with unit magnification therefore it is not clear that they are usable as they are in seekers. We will consider first the photographic singlet¹⁴ which could be used to image a target within a seeker.

Consider a thin radial gradient index lens in air, as shown in Fig. 6, with the index of refraction given by

$$n(r) = N_0 + N_1 r^2 + N_2 r^4 + \dots, \quad (4)$$

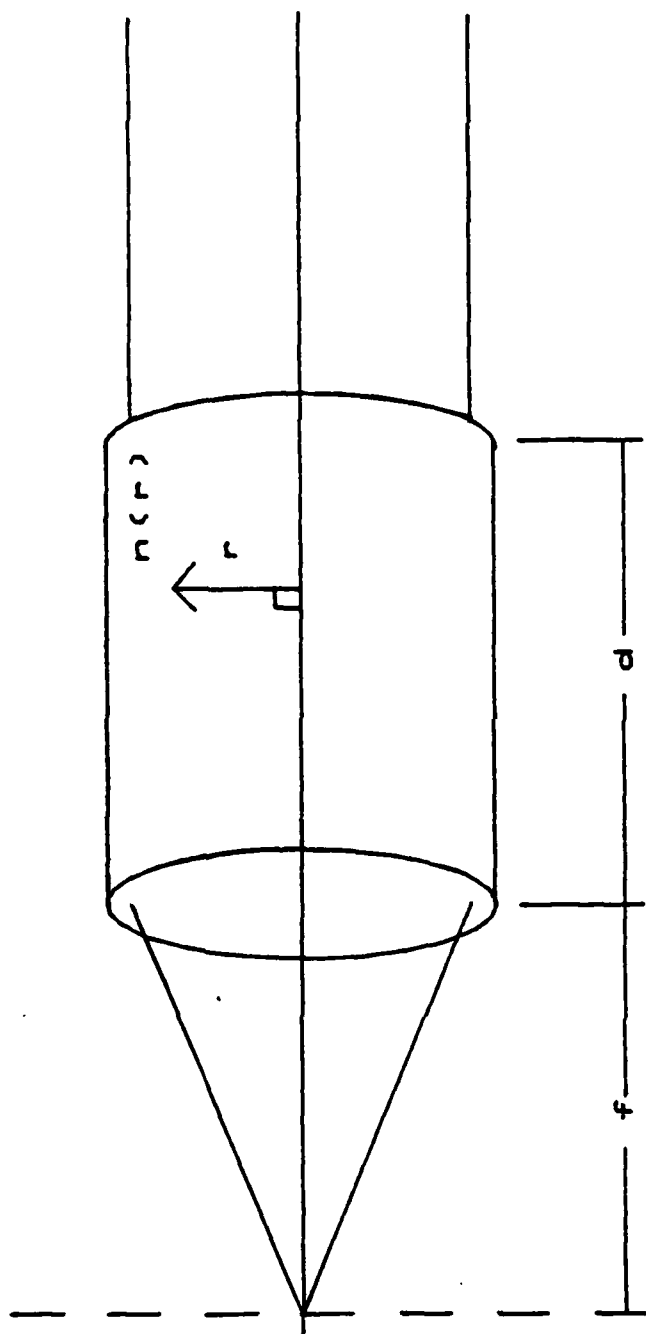


Fig. 6. Diagram of a photographic singlet.

in which r is the radial distance from the optical axis of the lens. If the object plane is at infinity and the thickness of the lens d is small then the focal length (i.e., distance from the lens to the image plane) is given to a good approximation by

$$f = -1/(2N_1 d). \quad (5)$$

We see that the focal length can be decreased by increasing the length of the lens. This also holds true in some thicker gradient index lenses as, for example, the lenses in the Selfoc array. However, as the lenses are made much thicker the size of the field illuminated by the lens decreases. Thus in an array of lenses there appears to be a trade-off between short focal length and resolution. Quite possibly a careful study of insect compound eyes could indicate to us how natural selection has coped with this trade-off.

The Selfoc array is interesting for what it tells us about gradient index lens arrays. These arrays have been studied at some length because of the interests of the copier industry.¹⁵ A diagram of a single index fiber from an array is shown in Fig. 7.

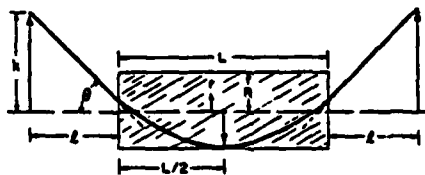


Fig. 7. Diagram of a gradient index fiber from a Selfoc array (from Ref. 14).

The array is designed to image, at unit magnification, between a pair of planes located a distance l on either side of the lenses as shown in the figure. Thus the total conjugate distance TC between the object and the image planes is important in this application, and gives a measure of the size of this imaging device. Also of importance is the maximum height k of the field range that can be imaged through the lens. The variation of these parameters with fiber length L is plotted from theoretical analysis of a typical Selfoc fiber in Fig. 8. Notice, as was the case with the photographic singlet, the focal length (i.e., the total conjugate distance TC) decreases with increased thickness L , but so does the field range. In an imaging array it is the field range that determines the number of lenses that contribute light to a single photoreceptor, and hence the effective aperture seen by that photoreceptor, and hence the diffraction limit to resolution. The resolution of this Selfoc array has been measured and the MTF determined for two different fiber lengths. This data, shown in Fig. 9, indicates that the resolution is actually better with the longer fibers. Clearly diffraction alone does not determine the resolution limit for these fiber arrays. Lamal¹⁵ concludes that other effects such as off-axis spot growth, fiber misalignment, variations in N_1 , and chromatic aberrations must be important. It appears clear that the commercially available fiber lens arrays are not very high quality relative to simple lenses.

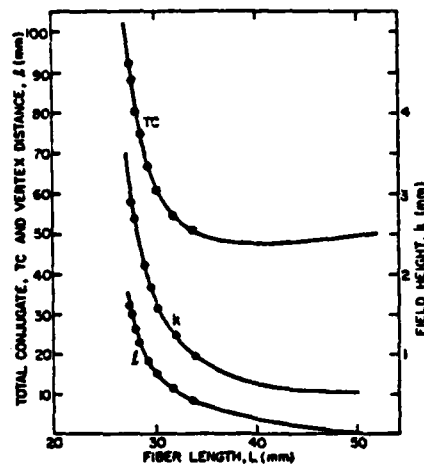


Fig. 8. Vertex distance l , total conjugate distance TC , and field height h , as a function of fiber thickness L (from Ref. 15).

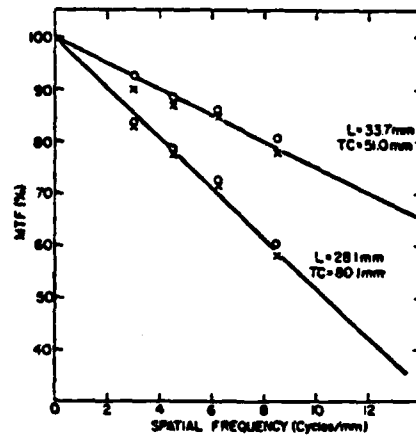


Fig. 9. MTF for a Selfoc array measured by imaging Ronchi rulings (from Ref. 15).

V. Conclusions

It appears that apposition compound eyes are not very promising for application to smart sensors because of their inherent low resolution and sensitivity. The superposition compound eyes might be of more interest if high quality gradient index lens arrays could be obtained in sufficient quantity. It does not appear that this is now the case, but one could hope for an improvement in technology. Some features of insect eyes such as the corneal nipples, and tracheole layer might definitely be of some value in systems design. The present state of knowledge of compound eyes is far from complete. The true functional operation of the clear zone eyes is not a matter of total agreement between all biologists. We will undoubtedly learn a lot about both eyes and gradient index lens fabrication in coming years which might be of vital interest to design engineers. Funding for research in these areas would of course be essential to assure this possibility. However, in this author's opinion these are now areas for basic research not development.

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